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The origin of collapse features appearing in a migrating parabolic dune along the southern coast of Lake Michigan

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A B S T R A C T

Dune decomposition chimneys are collapse features formed when migrating dunes encroach on a forest and buried trees subsequently decay, leaving a temporarily stable open hole. The recent appearance of holes on the stoss slope of Mount Baldy at the Indiana Dunes National Lakeshore provided an opportunity for study of such features. Mount Baldy is a large parabolic dune that is rapidly migrating onshore over a late Holocene landscape with stabilized relict parabolic dunes that supported oak (*Quercus* spp.) trees visible on the 1939 aerial photo. Individual holes were mapped to locations on the dune surface that would directly overlie the arm of a buried relict parabolic dune. Analyses of buried trees and surrounding sediment indicated that saprotrophic wood decay fungi continue to actively decompose trees after burial and biomineralization of a calcium-carbonate-rich cement occurs at the contact between organic material and sands. Scanning electron microscopy of the cement showed neoformed authigenic minerals and organic structures consistent in morphology with fungal hyphae. We propose that, within the dune, portions of the decayed trees progressively collapse and infill, and open holes are temporarily stabilized by the calcium-carbonate-rich cement. Further, holes can exist undetected at the surface, covered by a thin veneer of sand. Migrating dune systems are observed in many coastal and inland areas. Ongoing work must address the relative contributions of individual environmental factors on the formation of dune decomposition chimneys, including the biomineralization of cement, sand mineralogy, rate of dune movement, tree species, climate, and the composition of fungal communities.

1. Introduction

Narrow and temporarily stable holes (<30 cm in diameter) are forming on the stoss slope of a large coastal parabolic dune that has migrated inland over a forested late Holocene landscape along the southern coast of Lake Michigan (Fig. 1). The discovery of the holes at Mount Baldy in the Indiana Dunes National Lakeshore made world news when a six-year old boy was rescued safely after being buried under approximately 3.3 m of sand for more than 3 h in July, 2013 (Sabar, 2014). Upon arriving at the site there were no obvious signs of disturbance at the surface to suggest a collapse of sediment. But the boy's friend who was present at the time reported that they had seen an open hole, went to investigate its depth, and the boy slid out of sight into the hole which immediately infilled with sand. With the focus on search and rescue, no photographs or measurements were collected at the accident site to aid in the investigation of the hole's origin, and the excavation area was immediately backfilled for safety. Emergency responders reported finding other holes radiating toward the main vertical hole from which the boy was rescued. They described a pattern of void development similar to limbs branching from a tree trunk but no organic material was recovered or clearly observed at that time. Physicians hypothesized that there must have been an "air pocket" inside the dune that sustained the boy during the time of burial. At the time this study was completed, nine additional holes had been identified on Mount Baldy. The incident and detection of additional holes raised important questions about our understanding of the internal processes of migrating dunes. How could narrow holes form at various orientations and maintain an open structure to a depth of several meters in unconsolidated sediment? What happens to organic material, specifically, trees, that are buried by encroaching dunes? Was this an isolated incident, or have similar holes been observed in other dune systems? The purpose of this contribution is to present a mechanistic model for the formation of voids in actively migrating dunes; features

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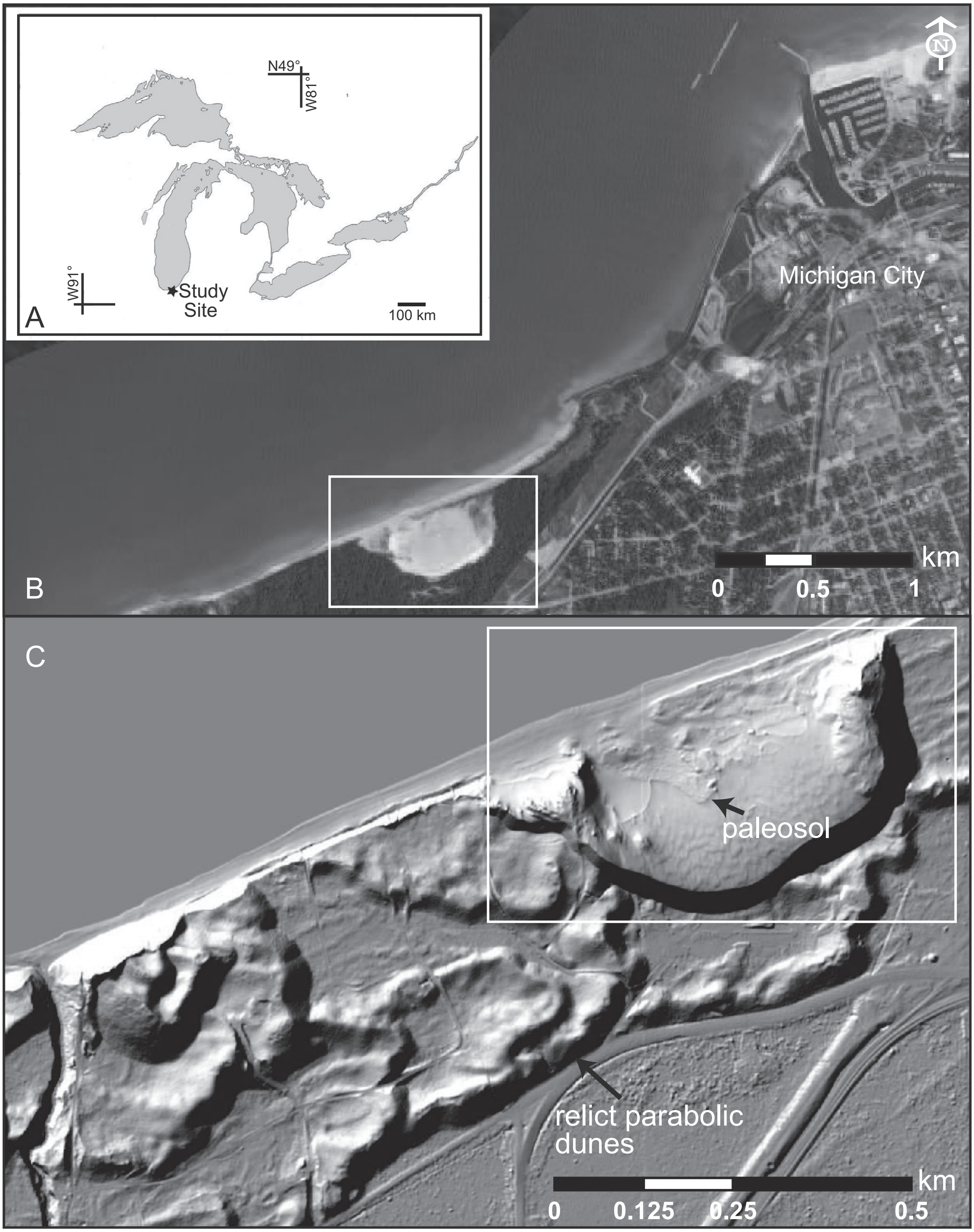

Fig. 1. Location of the study area; (A) within the Great Lakes region; (B) on aerial photo showing the Mount Baldy dune (white box) and Michigan City harbor structures; (C) close up 2013 LIDAR view of the Mount Baldy dune.

that we will subsequently refer to as dune decomposition chimneys.

The encroachment of mobilized dunes on forested landscapes is not an uncommon phenomenon and is observed in both coastal and inland dune systems around the world. In fact, Cowles (1899) described and photographed the encroachment of dunes on forests dominated by jack pine (*Pinus banksiana*) and black oak (*Quercus coccinea tinctori*) at the Indiana Dunes State Park; he concluded that the fate of the trees is an "inevitable" death dependent only the rate of the dune's advance. But migrating dune systems are well researched in coastal areas such as the Walking Dunes of Napeague, New York (Girardi and Davis, 2010), Jockey's Ridge, North Carolina (Mitasova et al., 2005), Atalaia Beach in equatorial Brazil (Buynevich et al., 2011), and along the Oregon coast

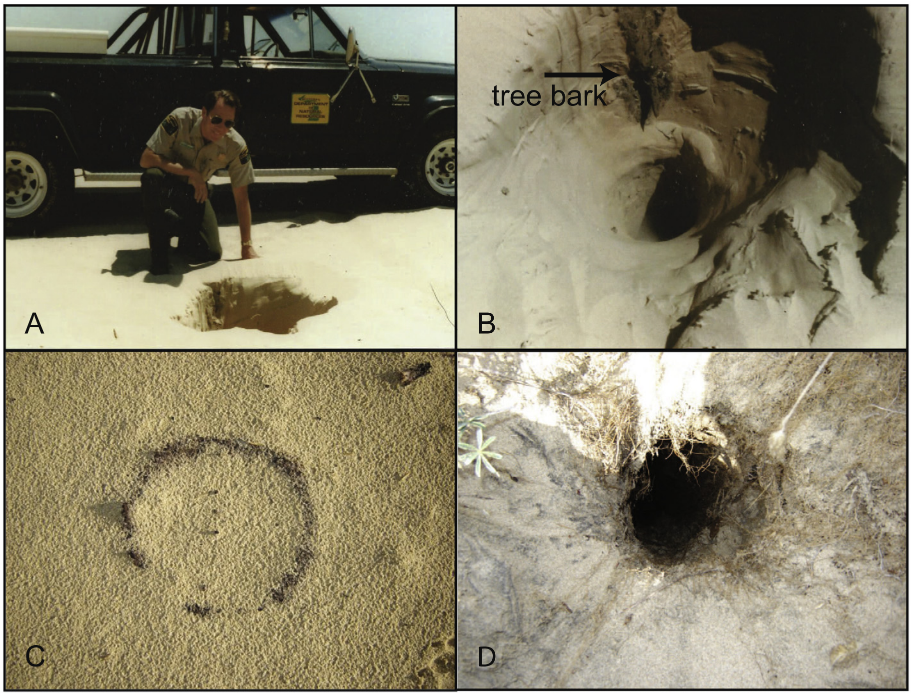

Fig. 2. Photographs of (A) hole found at Silver Lake State Park, Mears Michigan in 1985 with a pine limb visible in photo (B) (Photos courtesy of Peter LundBorg); (C) A "tree ring" and (D) hole observed at the ground surface of migrating dunes at Oregon Dunes National Recreation Area, Florence, Oregon (Photos courtesy of Dina Pavlis, http://alottasand.com).

(Hart and Peterson, 2007). Although these recent studies used trees as tools for establishing chronologies and rates of dune advance, the possible impacts of decomposing vegetation after burial on the internal stratigraphy or morphology of the dune were overlooked. Consequently, the results of our present study could have widespread implications for migrating aeolian systems worldwide and may introduce a previously unreported geologic hazard.

Anecdotal evidence, including photographs and personal accounts, suggest that similar holes or voids do occur in other migrating dunes. The clearest data come from shifting dunes at Oregon Dunes National Recreation Area in Florence, Oregon (Fig. 2). In her guidebook and website (www.aLottaSand.com), author Dina Pavlis (2008) presents photographs of features she terms "tree rings" and "tree holes" that are presumed to develop from buried trees. In Ken Kesey's, 1964 fictional novel *Sometimes a Great Notion*, the character Leland is a young boy who falls into a feature called a "devil's stovepipe." Uncle Hank explains "*You see, bub, this here was a pine forest a long, long time ago. These dunes didn't useta be here, just trees. But the winds kept bankin' the sand higher and higher and finally covered up the forest. Clean to the top of the trees. And the trees eventually rotted out, leaving these hollows where they useta be, maybe just barely covered at the top*". The setting for the novel is the northern Oregon coast, which includes the dune systems near Florence. Retired Park Manager Peter LundBorg provided pictures of a pine limb protruding from a hole found in 1985 at Silver Lake State Park in Mears, Michigan (Fig. 2). He commented that he always thought the formation of these holes was "common knowledge" and standard procedure at the park was to "fill in holes before anyone had a mishap." Personal communications with personnel and residents in Oregon and Michigan suggest that observed holes were small in diameter and generally were regarded as more of a tripping hazard than a serious danger. Unfortunately studies of the dimensions, formation, distribution, or persistence of such holes in migrating dunes are not found in the peer-reviewed scientific literature.

The recent discovery of holes at the Mount Baldy dune offers the first opportunity to directly study these collapse features. When the accident occurred in 2013, alternative hypotheses for the formation of the holes were considered, including: (1) the collapse of an underlying structure or an abandoned well where buildings once stood, (2) collapse due to groundwater piping through the underlying clay layer, and (3) internal instability resulting from suffosion. Moreover, the holes appeared similar to those that we observed forming in the winter season through niveo-aeolian sedimentary processes. But the appearance of holes in the summer season quickly dismissed the notion that the collapse features were related to niveo-aeolian processes. The uniform grain size of Mount Baldy disputes the hypothesis that collapse was caused by the seepage-driven transport of fine sediment or suffosion. The fact that holes continued to appear is strong evidence against the idea of the collapse of buried structures. This paper: (1) explains the pattern of holes in relation to the buried late Holocene landscape, (2) identifies an authigenic carbonate-rich cement in the sands that contact buried trees and may lend stability to the hole walls, (3) describes fungal activity observed in buried trees as evidence of the continued decomposition of trees after burial, and (4) investigates decomposition patterns in recently felled black oaks to formulate a model for hole formation as collapse features resulting from the in situ decomposition of buried trees.

2. Study area

Located within the larger coastal dune system that extends from Gary, Indiana, along the southeastern Lake Michigan shoreline, Mount Baldy is one of many coastal features and deposits associated with the Nipissing phase of ancestral Lake Michigan and post-Nipissing nearshore and onshore processes (Fig. 1) (Thompson, 1992). Within the modern dune system, individual dunes, including Mount Baldy, are considered compound and complex parabolic dunes with blowouts, according to the classification by McKee (1979). The dunes have long-axis orientations consistent with the predominant north-to-northwest onshore wind direction (Fig. 1). Mount Baldy is located ~2.5 km west of Michigan City, Indiana, where the navigational harbor structures block the natural westward transport of longshore drift, restricting sediment supply to the coastal zone (Chrzatowski et al., 1994; Shabica and Pranschke, 1994; Wood and Davis, 1986). This promotes ongoing erosion at the shoreline that liberates vegetated sediment and initiates dune blowouts and onshore migration. At Mount Baldy the combination of sand starvation, ongoing shoreline erosion, strong onshore winds, and heavy pedestrian traffic combine to force southward dune migration.

Having an area of ~0.16 km^2 Mount Baldy is generally considered the largest active blowout in coastal dunes along the southern shore of Lake Michigan (Kilibarda and Shillinglaw, 2014). Thompson (1989) shows a contact between aeolian and Nipissing nearshore deposits at an elevation of 183 m, indicating that the modern Mount Baldy dune consists of aeolian deposits that are ~26 to 37 m in thickness and overlie waterlain sediments. The exposure of a paleosol with protruding tree trunks on the stoss slope indicates that the aeolian sands of modern Mount Baldy overlie a previously stabilized late Holocene landscape. Although Gutschick and Gonsiewski (1976) recognized the prominent soil as a former forest layer, Arbogast et al. (2002) further interpreted the paleosol as an Inceptisol that began forming ~2000 cal yr B.P. and was buried within the past ~500 years, consistent with the regionally relevant Holland Paleosol. This soil is found in many places along the southeastern shore of Lake Michigan (Arbogast et al., 2004), and is exposed by shoreline erosion. The 2013 LIDAR data reveal that Mount Baldy is migrating over the north arm of a compound nested parabolic dune that has an east–west long-axis orientation indicative of predominant westerly winds (Fig. 1). Using optical dating, Argyilan et al. (2014) established that this inland system of east–west-oriented relict dunes had stabilized by ~3500 years ago during a period referred to as the post-Nipissing Interlude (Hansen et al., 2010). The exposure of the paleosol on the north stoss slope indicates that the dune's movement has now eroded into this stabilized arm. A comparison of 1939 and 2013 aerial photography documents the rapid southward advancement of Mount Baldy over a recently forested landscape (Fig. 3). Hence the modern Mount Baldy is composed of aeolian sands mobilized by recent shoreline erosion and deposited atop previously stabilized lower relief dunes. These lower relief dunes supported an oak (*Quercus* spp.) forest growing on a the late Holocene paleosol, visible in the 1939 aerial photograph (Fig. 3).

3. Methods

3.1. Site analysis

The Mount Baldy site was closed after the 2013 incident and access was restricted to National Park Service (NPS) staff and individuals involved in the research of the holes. Other holes included in this report were found primarily by staff as they conducted restoration work on the dune and during occasional surveys by researchers. When holes were found, personnel collected GPS coordinates, photographs, and dimensions, if possible (Table 1). Once disturbed, the holes rapidly infilled with sand, limiting further study. It is likely that more holes have formed but have gone undetected because of their rapid collapse and the fact that access to the site has been restricted since the summer of 2013.

The GPS locations of the ten documented holes were referenced to the 1939 aerial photograph, which is the earliest available image of the study site. Independently of those holes, we used organics visible at the surface to locate buried trees that were then partially excavated to collect samples of wood, the surrounding sediment, and fungi adhered to and within the wood. Excavations were photo documented.

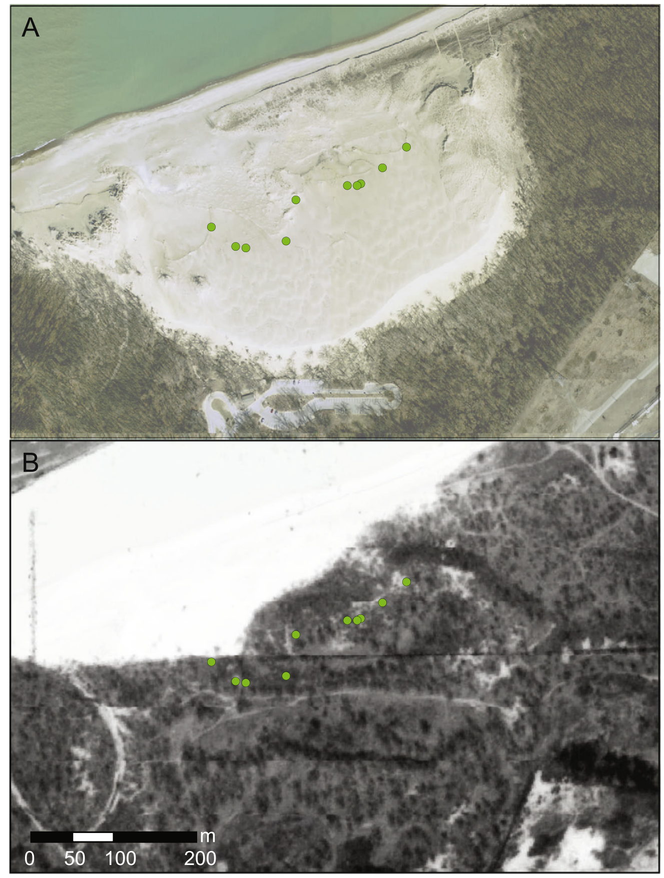

Fig. 3. Aerial photographs showing the position of holes (green circles) relative to the (A) 2013 and (B) 1939 imagery.

3.2. Mineralogical analyses of sediments surrounding buried trees

To understand how the holes might be stabilized, we collected samples of altered sediment observed in contact with the buried trees and compared them to proximal unaltered sediment using scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS). Additional sediment samples were collected to constrain sources of carbonates in the system. The samples included: (1) a fossiliferous clay that underlies the gravels and sands deposited during the lake-level rise to the peak of the Nipissing Phase (c.f., Gutschick and Gonsiewski, 1976; Thompson, 1989), and (2) dried pedogenic laminae that were evident only after a major storm on October 31, 2014, in layers interbedded between sands of the stoss slope of the dune. Grains from individual samples were mounted on carbon sticky tabs adhered to aluminum stubs. Samples were investigated using a Zeiss VP35 field emission scanning electron microscope under variable pressure conditions with nitrogen as the compensating gas. An operating voltage of 20.00 kV was used and a working distance of 8.5 mm was set for optimum EDS operation.

3.3. Fungal analyses

Macroscopic, microscopic, and molecular methods were employed to examine four separate wood sections collected from inside the Mount Baldy sand dune for the presence of fungi. The

Table 1
Available data for dune decomposition chimneys discovered on Mount Baldy, Indiana Dunes National Lakeshore, Indiana.

Feature ID*	Northing	Easting	Diameter (cm)	Depth (m)	Elevation change (m) (2010–2013)	Additional comments
MB2013.07.12	4617422.16	505840.19	N/A	3.3	−2.26	Visible at surface. Initial hole associated with the accident
MB2013.08.12	4617495.82	505960.03			−2.3	Found by park staff. Wood recovered nearby. Smaller than hand
MB2014.03.18	4617430.32	505887.68			−2.38	Found by park staff. Bark recovered from edge of hole. Smaller than hand
MB2014.04.24	4617541.33	506029.87			−1.42	Found by park staff. Smaller than hand
MB2014.07.28	4617516.79	506001.57			−1.98	Found by park staff. Not visible at surface. Smaller than hand
MB2014.07.30	4617478.96	505899.27			−0.40	Person fell into knee. Not visible at surface. Northernmost hole
MB2014.08.13	4617498.04	505975.07	22	1.51	−2.11	Todd Thompson uncovered while walking. Not visible at surface. Wood recovered. Dip −79
MB2014.11.07	4617495.75	505971.64	26	1.8	−2.18	Erin Argyilan fell in while photographing uncovered limb. Not visible at surface. Diameter 26 × 16 cm. Dip −66
MB2014.11.10	4617423.92	505828.19			−2.24	Found by park staff. Deeper than shovel handle. Smaller than hand
MB2015.04.29	4617446.84	505799.58	5.1	0.31	−1.71	Found by park staff

* The nomenclature of the feature ID is the year.month.day of discovery.

wood sections were first examined visually without the aid of a microscope, following a similar approach taken in Norris et al. (2013). Each wood section was examined closely for the presence of fungal hyphae, mycelium, and rhizomorphs, structures that can often be seen without the aid of a microscope.

A subset of the fungi observed by macroscopic means were examined using, first, a dissecting microscope (up to 10× magnification) and then with a compound microscope (up to 1000×). For the latter observations, a flame-sterilized set of probes and forceps were used to select portions of fungal structures, which were then placed into a drop of sterile water or KOH on a microscope slide and covered with a cover slip. Portions of these fungi were also placed into sterile 1.5-mL microtubes for molecular-based identification. The DNA methods used follow Avis et al. (2008) and targeted the ITS gene region that is the DNA "barcode" or fungal-specific DNA marker (Schoch et al., 2012). Tissues were subject to DNA extraction (Sigma's REDExtract-n-Amp kit), followed by the Polymerase Chain Reaction (PCR) (using primers ITS1F and ITS 4) (White et al., 1990) and the Sigma kit reagents and Sanger DNA sequencing (using ABI Big Dye and the ITS1F primer). Sequences were screened on an ABI3730 DNA Analyzer at the Pritzker Laboratory of Molecular Evolution and Systematics and the DNA Discovery Center at the Field Museum of Natural History. Sequences generated were then examined by the Basic Local Alignment Search Tool (BLAST) and identities of fungi were inferred by examining the BLAST results (http://blast.ncbi.nlm.nih.gov/Blast.cgi).

3.4. Patterns of internal decomposition in black oaks

The restoration of a remnant black oak savanna in Miller Woods, Gary, Indiana, ~32 km west of Mount Baldy, presented the opportunity to investigate decomposition patterns within recently felled trees. We analyzed 56 trees that showed evidence of internal decomposition for the following metrics: diameter at what would be breast height (1.5 m) from the base, height to branching, and diameter of internal decomposition versus external diameter at 1-m intervals. The aim was to examine whether decomposition rates appear constant or are variable throughout the trunk of the tree. The pattern of internal decomposition throughout the length of the trunk may affect the timing and development of holes associated with an individual tree. Decomposition within branches was not assessed.

4. Results and discussion

4.1. Historical dune migration and the distribution of holes

As the modern Mount Baldy dune form advances to the south, it is migrating over a stabilized late Holocene landscape that consists of east–west-oriented parabolic dunes. Therefore, the modern Mount Baldy consists of recent dune sands mobilized by historical shoreline disturbance that are deposited atop a relict dune system that is stabilized by the observed paleosol. Ten open holes have been documented at Mount Baldy since July 2013, including the one associated with the initial incident (Table 1). Referencing the GPS coordinates with aerial photography revealed that the holes observed on the stoss slope of Mount Baldy consistently occurred landward (south) of the exposed paleosol and emergent stumps (Fig. 3). This indicates that holes are forming in the sand layer that directly overlies the north arm of the relict dune that was buried by recent (historical) shoreline erosion. The paleosol yielded an age of 3690 ± 30 ^{14}C yr BP (4080–3980 cal yr BP) on bulk organic material (wood), that is consistent with ages for similar local east–west-oriented dunes (Argyilan et al., 2014) and organic material, primarily charcoal and wood, collected from the soil (Arbogast et al., 2002). We are not suggesting that the buried trees are late Holocene in age, but rather that the oak (*Quercus* spp.) forest observed at the site in the 1939 photograph was growing on the ~3500 year old paleosol (Fig. 3). While we cannot estimate the state of decomposition of the trees at the time of burial, the decomposition of oak trees over ~70 years is reasonable, considering estimated species-specific rates (Johnson et al., 2014; Schowalter et al., 1998).

The changing thickness of the sands overlying the buried trees, caused by ongoing migration, is likely another key factor in the development of the holes. The stoss (north) slope is dominated by deflation; sand that is transported over the crest is deposited on the slipface, moving the entire dune form southward over time. At the location of each of the ten holes we compared the surface elevation from the 2010 digital elevation mode (DEM) to the same points on the 2013 DEM (Table 1). The data show that, as Mount Baldy migrates to the south, the thickness of the sand at each point, and ultimately over the exposed paleosol, has decreased by a minimum of 0.40 m to as much as 2.38 m. The data clearly reflect that, at these fixed points the stoss slope is lowering onto what would be the canopy and upper trunks of the buried trees rooted on the underlying relict dune.

Fully buried trees can often be located by emergent stumps or expressions of organic material at the surface. Stumps are desiccated and hardened above the ground surface and are commonly referred to as "ghost forests." In the subsurface, the same trunks are spongy and decomposed in the moist conditions. Excavation of buried trees revealed fungal decomposition of the core of limbs and trunks (Fig. 4). Fungal hyphae were also visible at the outer bark of buried trees that was in contact with surrounding sediment. At three locations, decomposing limbs were excavated and observed to terminate into open holes. We conducted a survey after a major storm on October 31, 2014, and found the decomposing limb of a previously buried tree that was now completely

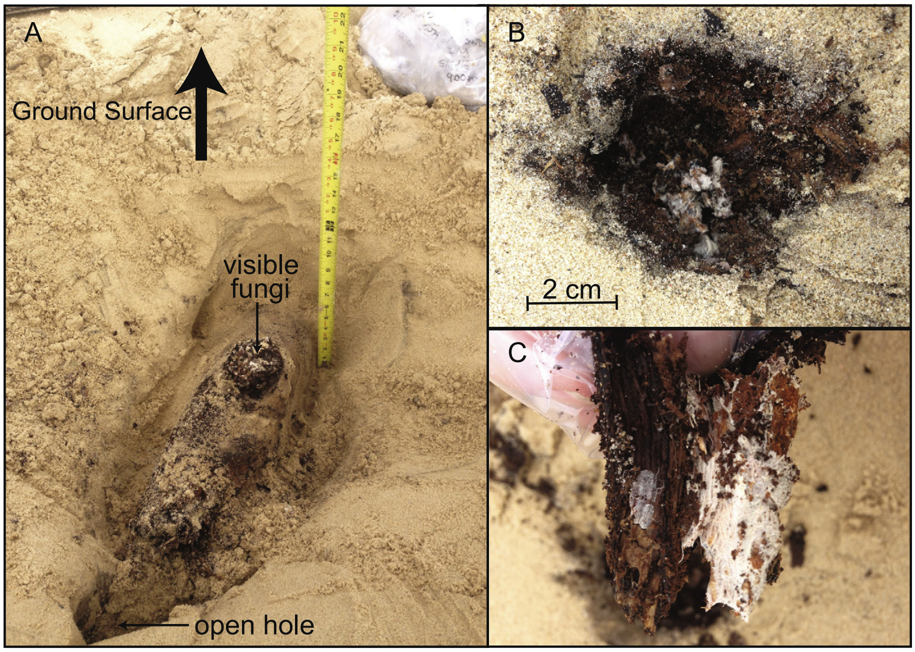

Fig. 4. Photographs of (A) excavated tree limbs with a branch terminating into a hole; (B) expression of buried limb at the surface prior to excavation, with fungi visible in the center of the limb; (C) fibrous fungi from center of decomposing limb.

exposed along the surface of the stoss slope to the south of the paleosol (Fig. 5). The limb continued vertically into a hole that measured 26 × 16 cm in diameter and ~2.4 m in depth (Fig. 5). This was the clearest evidence we had observed of a tree limb connecting to a vertical trunk that was decomposing and producing a stabilized deep hole. Fungal hyphae were visible in the decomposed organic material (Fig. 5). Interestingly a mineral "crust" was observed on the exposed organic material after the storm, and dried pedogenic laminae (1–3 mm thick) were observed protruding from the stoss slope of the dune (Fig. 5). The significance of these mineral deposits to the formation and stability of the holes is explored below. This hole was not visible at the surface and was exposed only when stepped on accidently; contrary to our early assumptions that the holes are always open and visible at the surface. Four holes were discovered when people stepped into them during surveys. These observations show that a veneer of sand can conceal an underlying void that has formed and remained somewhat stable, undetected beneath the dune surface. Because we have directly observed decomposing tree limbs and trunks terminating into holes, we refer to the collapse features as "dune decomposition chimneys", recognizing that partial decay can produce decomposition tunnels that are not open at the dune surface, and that final infilling leaves temporarily visible depressions or dimples in surface sands.

4.2. Mineralogical results of sand analysis and the origin of a carbonate-rich cement

A distinct color change was evident in sands that were within ~2 cm of a buried limb and those collected at >2 cm (Fig. 6). The mineralogy and texture of sands collected that were in contact with buried tree limbs were compared to those of adjacent unaltered material. SEM investigation indicates that a mineral "cement" is present in the altered sand collected in contact with buried tree limbs (Fig. 7). Detrital sand grains are angular to moderately well-rounded and have mineralogical contents dominated by quartz, K-feldspar and lesser amounts of albite. Overgrowths of calcium-carbonate-rich cement are common. This cement is characterized by wisplike textures of subhedral crystals that exist as fine aggregates. Higher-magnification imaging of surfaces of the calcium carbonate cement material show an abundance of euhedral dogtooth crystals with $\{21\bar{3}1\}$ expressed, commonly 1–4 μm in diameter, which is indicative of neoformed authigenic minerals. Individual crystals appear to vary in average diameter from approximately 2 μm–100 nm. All cement material had Ca, C, and O in appropriate ratios consistent with a calcium carbonate polymorph; however, oxygen contributions to these EDS spectra are also derived from substrate silicate minerals. EDS spectra are consistent with a calcium carbonate phase; however, minor amounts of Mg, Al, and Fe are common (Fig. 7). The cement shows direct contact with grains in SEM images, although much of the cement has detached from grains. Some complex textures are interpreted as organic in origin; this suggests a biologic origin or partial contribution to the mineralization by microbial activity, presumably the observed fungi (e.g., Fig. 7D).

Numerous examples of tube structures were observed in the altered sand material, and smooth spheroidal particles were observed less commonly. Tubular structures commonly vary in diameter from ~1.5 to 12 μm and from 20 to 70 μm in length. Spheroidal particles are commonly 10 to 16 μm in diameter; some particles are nearly spherical, whereas others are more oblate. The textures of observed tubular structures are consistent with known morphologies of fungal hyphae (Harris, 2008) while spheroidal textures may represent fungal spores (Nilsson, 1983) (Fig. 8). Both biogenic structures are intimately associated with the calcium-carbonate-rich cements; most importantly, there appears to be a mutually exclusive relationship. The biogenic textures are not observed in the clean sand, which strongly suggests that the biogenic structures are specifically associated with the crystallization of the cement.

SEM investigation of the unaltered sand shows that it is dominated by quartz (~70%) and has lesser amounts of K-feldspar (10%) and dolomite (15%) (Fig. 9). Quartz grains are commonly subangular to well-rounded and are 0.15–0.40 mm in diameter. Quartz grains are free of any calcium-carbonate-rich cement, although minor amounts of aggregates of Fe–Al oxides were observed on some grains. K-feldspar grains are often more rounded and more extensively pitted, which indicates chemical alteration from

Fig. 5. (A) A tree limb exposed on the stoss slope after a major storm extends into a vertical hole that measured 2.4 m in depth and 26 × 16 cm in diameter. A carbonate precipitate is visible on the subaerial surface of the limb and as horizontal ''laminae'' on the stoss slope. (B) The tree limb connects to the trunk which dips to the north at an angle of 66° with the dune's stoss slope. Fungal hyphae were visible in the decomposing wood upon excavation (arrows).

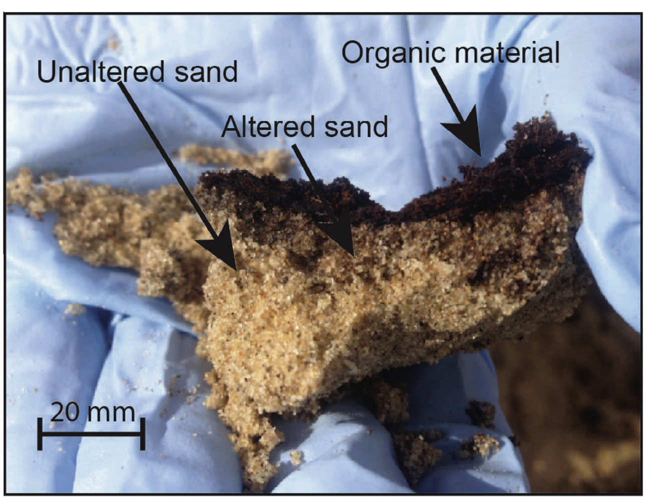

Fig. 6. Photograph showing the altered sand that occurs in contact with the bark of buried trees and proximal unaltered sand.

weathering. Some of these grains have minor amounts of calcium-carbonate-rich overgrowth material; however, unlike in the altered sands, these textures are largely isolated masses a few micrometers in diameter that cover approximately 1 percent of individual K-feldspar grains. Detrital dolomite grains exhibit typical rhombohedral or distorted rhombohedral cleavage. These grains have moderate to extensive calcium carbonate-rich cement material associated with them as coatings, which are commonly 10–15 μm thick. One unusual feature of some dolomite grains is that the EDS spectra show up to several weight percent of sulfur and chlorine. One possible reason for this is that sulfur and chlorine associated with the overgrowth texture of dolomite in the unaltered sand results from interactions of porewater contaminated with atmospheric H_2SO_4 and HCl, potentially derived from nearby industrial coal stacks along the southern shoreline of Lake Michigan.

The mineralogy of the unaltered sands is broadly consistent with the local geology and the classic descriptions of sands from Lake Michigan (Pettijohn, 1931). However, mineralogical results and textural analyses indicate that the authigenic calcium-carbonate-rich cement is forming at the contact between buried trees and adjacent sands. This spatial association points to the cement originating from a biogeochemical reaction with fungi that are actively decomposing the organic material. Fungal hyphae are known to be able to produce and exude compounds, such as calcium oxalates in quantity (Franceschi and Loweus, 1995). Biomineralization of calcium carbonate has been widely studied (cf., Whiffin et al., 2007; De Muynck et al., 2008; Burbank et al., 2011; Achel et al., 2012), but little is known about the specific role of fungi (Li et al., 2014). Li et al. (2014) suggest that fungal hyphae provide nucleation sites for the precipitation of calcite minerals, but also recognize the contribution of soil bacteria in calcium carbonate biomineralization. What is most relevant to our study was the observation made by Whiffin et al. (2007) that noted a significant improvement in the strength and stiffness of an experimental column of sand resulting from microbial calcium carbonate precipitation. Their findings led them to propose that biologically induced calcium carbonate precipitation could be used as a geo-engineered method for improving soil strength (Whiffin et al., 2007; Li et al., 2014). The key factors that affect $CaCO_3$ precipitation include the concentration of calcium, the concentration of dissolved carbonate, pH, alkalinity, the medium composition, and the availability of nucleation sites (Li et al., 2014). The abundant fungi associated within and on the surface of buried trees would provide ample nucleation sites. Acids produced by decomposing oaks may influence the pH in sediments to facilitate dissolution of calcium carbonate. Dolomitic grains that accounted for ~15 percent of the unaltered sands at Mount Baldy may be a sufficient source of both calcium and carbonate. However, it is noteworthy that several additional sources of calcium and carbonate are affecting the Mount Baldy study site.

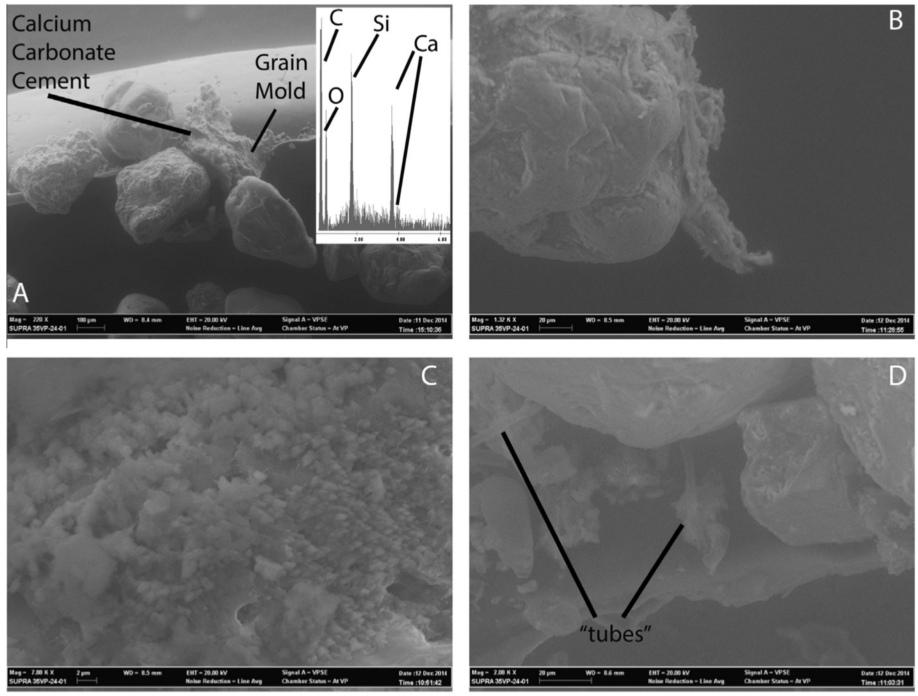

Fig. 7. SEM images of altered and partially cemented sand. (A) Low magnification image of grains with attached and broken cement showing intact grain molds. The scale bar is 100 µm. The EDS spectra is taken over the region labeled calcium carbonate cement and the Si peak is from adjacent quartz. (B) A higher magnification image showing the calcium carbonate cement material in intimate contact with K-feldspar. (C) Shown fine euhedral crystals that are 1 to 4 mm in diameter which are consistent with the dogtooth morphology of calcite. Such delicate textures are consistent with neoformed authigenic crystals. (D) Examples of "tubes" interpreted as fungal hyphae associated intimately with the calcium carbonate cement.

Additional sources of carbonate to the Mount Baldy system beyond the alternation of carbonate dune sands include local geologic and atmospheric sources. Discerning the exact contributions of these sources is challenging but evidence exists for contributions by both. Ongoing and extensive erosion of the modern beach has exposed underlying Ca and Mg-rich fossiliferous back-barrier lacustrine sediments ~0.86 m in thickness (Fig. 10). Flat, gravel-sized particles of this lacustrine sediment are actively transported up the stoss slope by onshore winds. These particles are easily subject to alteration in place to produce Ca and Mg-rich pore waters. Atmospheric precipitation at this site is an additional source of Ca and Mg to the dune surface. The 2013 annual gradient maps of precipitation-weighted mean ion concentrations available from the National Atmospheric Deposition Program show that northwest Indiana is an area of high Ca and Mg deposition, reporting Ca^{2+} concentrations $\geqslant 0.50$ mg/L and Mg^{2+} concentrations $\geqslant 60$ µg/L in the area of Mount Baldy (http://nadp.sws.uiuc.edu/). Additional evidence of atmospheric input to the system may be indicated by the observed sulfur and chlorine associated with the overgrowth texture of dolomite in the unaltered sands. A carbonate-rich "crust" was evident at the surface of Mount Baldy on exposed tree limbs and as pedogenic laminae protruding from the stoss slope immediately after the October 31, 2014 storm (Fig. 4). The additional environmental sources of Ca considered along with the lack of abundant carbonate (15%) in unaltered dune sand suggest that atmospheric precipitation is a major source of carbonate to the system. We propose that the authigenic carbonate cement observed in the SEM images of altered sand is a combination of in situ weathering of dolomitic sand grains and abundant Ca and Mg present in the pore water that preferentially moves vertically along conduits produced by buried trees.

4.3. Fungal analysis

Macroscopic observation showed structures that are interpreted as fungal in origin (hyphae, mycelia, rhizomorphs) on all wood sections we examined (Table 1). In some cases, fungal mycelium densely covered the examined sections (~0.025 m^2 average area estimate of four wood sections) while in some sections mycelium were less dense or absent. Fungal structures were found on the surfaces and growing into the inner portions of the wood sections.

With microscopic observation up to 1000×, all examined sections exhibited cellular forms and structures consistent with fungal morphologies. Long, filamentous tubular cells or hyphae were evident. In some cases, clamp connections were also observed (a structure only found in the Basidiomycetes, the fungal phylum of which most wood-rotting fungi). In addition to fungi, we saw some plant roots that appeared macroscopically similar to fungal hyphae but, on closer examination, had the cellular shape and tissue architecture (root hairs, cortex, stele) typical of plant roots. We observed several round structures that could be fungal spores or possibly cysts or eggs of insects.

Molecular results were consistent with our visual observations. Five samples collected from the wood sections that produced positive polymerase chain reaction amplicons produced sequences. When these sequences were compared to GenBank (a global genomic database) using BLAST, all sequences matched to fungi. Of these five, four matched to a saprotrophic Basidiomycete fungus in the genus *Lepiota* and another sequence was similar to an Ascomycete fungus in the class Leotiomycetes of unknown nutritional type.

Taken together, these results unequivocally indicate the presence of fungi in these samples. Further, fungal structures, such as hyphae, in the wood suggest they are active in the decomposition of wood. Hyphae are the structures wood-decomposing fungi use to explore suitable substrates and then use to exude enzymes for breaking down lignin and cellulose, compounds that compose wood (Alexopoulos et al., 1996). The decomposition of wood by fungi generally occurs in three stages or waves – an initial group of fungi involved with living trees, followed by fungi that attack

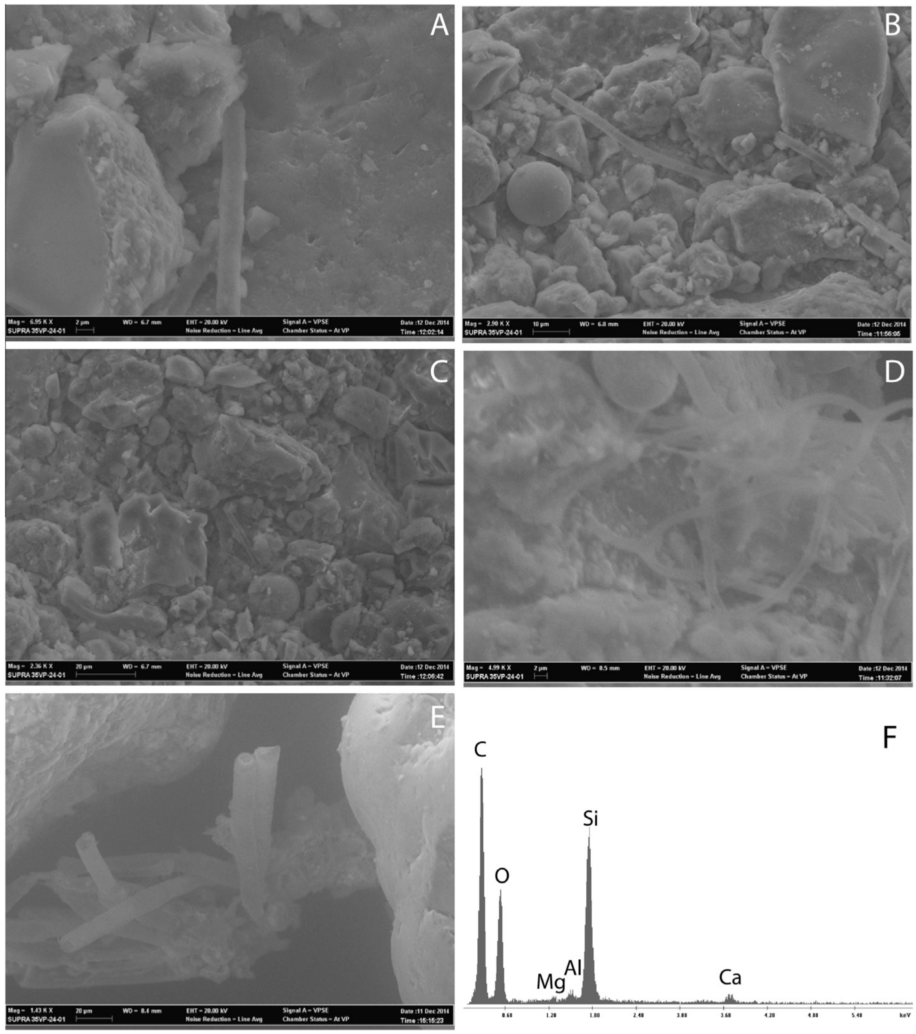

Fig. 8. SEM images showing tubes and round textures from cement regions and interpreted as biogenic. (A) A tube interpreted to be a fungal hypha approximately 3 μm wide. (B) Three parallel tubes interpreted to be fungal hyphae adjacent to a round particle interpreted to be a potential spore. (C) A tube in the center surrounded by calcium carbonate cement. (D) An anastomosing network of tubes that are interpreted as hyphae showing bifurcation. The upper region shows a round particle interpreted as a potential spore. (E) A cluster of tubes interpreted as fungal hyphae showing widths of approximately 8–10 μm and length of 50–70 μm. (F) A representative EDS spectra of spot analysis taken from tube structures.

wood after tree death, and, finally, a suite of residual decay fungi that complete the disintegration of wood into small particles of organic matter (Kubartova et al., 2015). The fungi we identified by DNA sequencing (e.g., *Lepiota*) are most likely members of this final suite of residual decayers (Vellinga, 2004). However, a diverse number of fungi are involved with decomposition. For instance, more than 200 species of fungi were found to be involved in the decomposition of oak wood debris when studied at a regional scale (Irsenate and Kutorga, 2006). Many more samples must be examined more exhaustively to piece together the broader picture of the fungal communities likely involved in the decomposition of the wood at Mt. Baldy.

Estimates of the rates of wood decomposition (Schowalter et al., 1998; Johnson et al., 2014) are consistent with the window of time it would take to decompose oak trees buried 70–80 years ago by Mount Baldy's advance. However, many questions remain. For instance, we cannot know the extent of decomposition that had already occurred within the trees when they were buried. Further, it is unclear whether the decomposition rate has been relatively constant or episodic since burial. Presumably environmental conditions (e.g. temperature, oxygen, moisture) in the dune are favorable for decomposition, because we have identified fungi in these wood samples; however, we do not know how these conditions have varied and what conditions might trigger rapid decomposition. Further examination is underway to understand more of the fungi involved and the potential for these fungi to decompose trees buried within a dune.

4.4. Experimental analysis of decomposition patterns in oaks

Our conceptual model illustrates how the shifting elevation of the stoss slope with dune migration leads to the exposure of the paleosol, the appearance of organic material, and the formation of dune decomposition chimneys at the modern surface (Fig. 11). We further hypothesize that the rate of internal decomposition must vary spatially within a buried oak tree, directly affecting the development and dimensions of a dune decomposition chimney, including its diameter, size, orientation, and depth. Tree limbs that intersect the surface may appear as small rings of organic material and ultimately produce holes that are somewhat narrow in diameter and shallow in depth. Most holes observed at the surface or in association with excavated trees at Mount Baldy were relatively shallow, open to depths of <1 m, suggesting that portions of the tree, rather than the entire tree form, progressively collapse

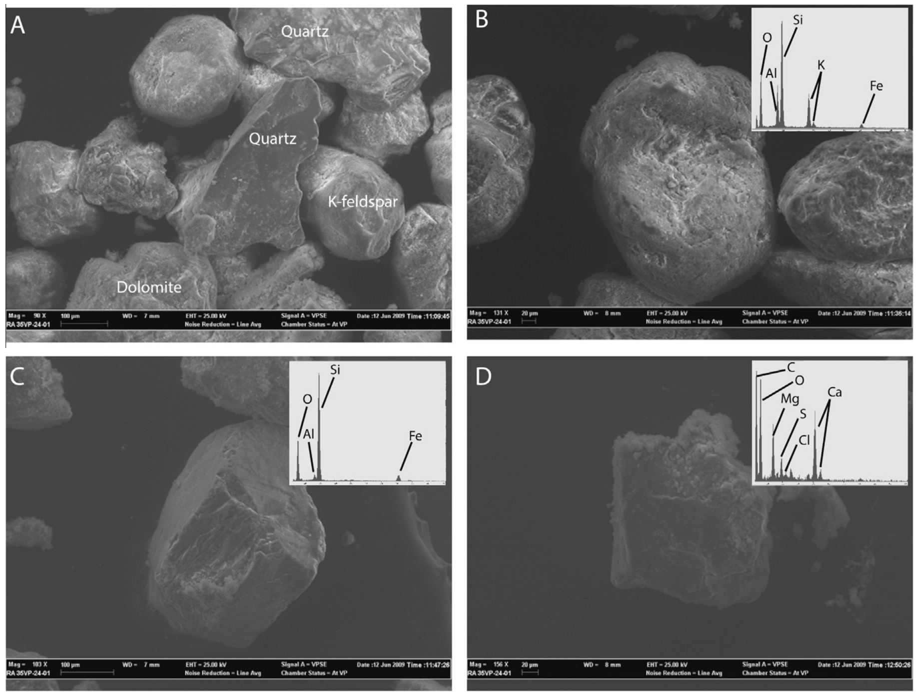

Fig. 9. SEM images and EDS spectra for unaltered sand adjacent to cement. (A) SEM image of typical sand grains showing morphologies of quartz, K-feldspar, and dolomite. (B) SEM image of a typical rounded K-feldspar grain with related EDS spectra with K, Al, Si, and O peaks labeled. Very minor amounts of overgrowths are evident. Fe is present and is interpreted as fine-grained iron oxides in the microtopography of the grain. (C) An example of an angular quartz grain and related EDS spectra showing minor Al–Fe oxide material on the lower portion of the grain. (D) Detrital subhedral dolomite grain showing rhombohedral cleavage. Overgrowths are common on this grain and on other detrital dolomite grains observed.

Fig. 10. Late Nipissing fossiliferous back-barrier lacustrine sediments underlying nearshore and aeolian sediments were exposed by shoreline erosion that occurred during a storm on October 31, 2014.

and then infill (Table 1). But the hole discovered after the October, 2014 storm shows that large diameter (>20 cm) dune decomposition chimneys can form when the stoss slope vertically erodes to intersect the trunk of a buried tree (Fig. 5). This is most likely the same scenario that produced the hole associated with the accident in July, 2013.

To better understand the pattern of decomposition within buried trees, we examined the external trunk diameter versus the diameter of internal decomposition in 56 recently felled black oak trees. The average external diameter was measured at what would be breast height – 1.5 m from the base. The average external diameter ranged from 14 to 50 cm, with an average of 28.7 cm. A dune decomposition chimney that formed from the decay of a vertically oriented section of the trunk of a black oak could, in fact, be large enough to be hazardous to even an adult, although no collapse features larger than 26 cm have been directly observed at Mount Baldy (Table 1). We found that 33 of the trees studied had measurable internal decomposition that was limited to <1 m in height from the base. An additional 15 trees had measurable internal decomposition that continued to <2 m in height from the base. In each of those trees the diameter of internal decomposition decreased between the 1-m and 2-m segments, suggesting that decay was progressing from the base up the trunk of the tree. This pattern of upward-progressing decomposition inside the trunk was also evident in two trees that showed decay extending to <3 m. Five trees exhibited measurable decomposition beyond 3 m. In those trees the diameter of decomposition was highly variable within the tree rather than showing progression vertically from the base. Also, where these trees had experienced damage from broken limbs or fire we observed areas of localized accelerated decomposition. Another tree showed no decomposition at the base but 15 cm of internal decomposition was measured at both the 1-m and 2-m heights.

The modern tree data further suggest a general pattern of internal decomposition in oaks that begins at the base and progresses up the trunk in unburied trees (Fig. 11). We can assume that many of the trees on Mount Baldy had similar patterns of internal decomposition at the time of burial. Once the dune's movement completely entombed the tree in sand, decomposition likely continued to progress up the trunk while fungi also spread throughout the tree. Post burial rates of decomposition then become highly variable within the trunk and limbs, likely depending on environmental conditions within the dune (e.g. moisture, temperature) and the size of the limb. Ultimately, decomposition progresses to the point where organic material collapses and the void is temporarily stabilized by the cement. Essentially the holes reflect the final collapse of the organic material or arrival at a decompositional "tipping point" for stability. This pattern of internal decomposition leaves the upper trunk and canopy somewhat stable within the confines of the inner dune and helps inhibit infilling of the underlying void by sand from above. The larger diameter

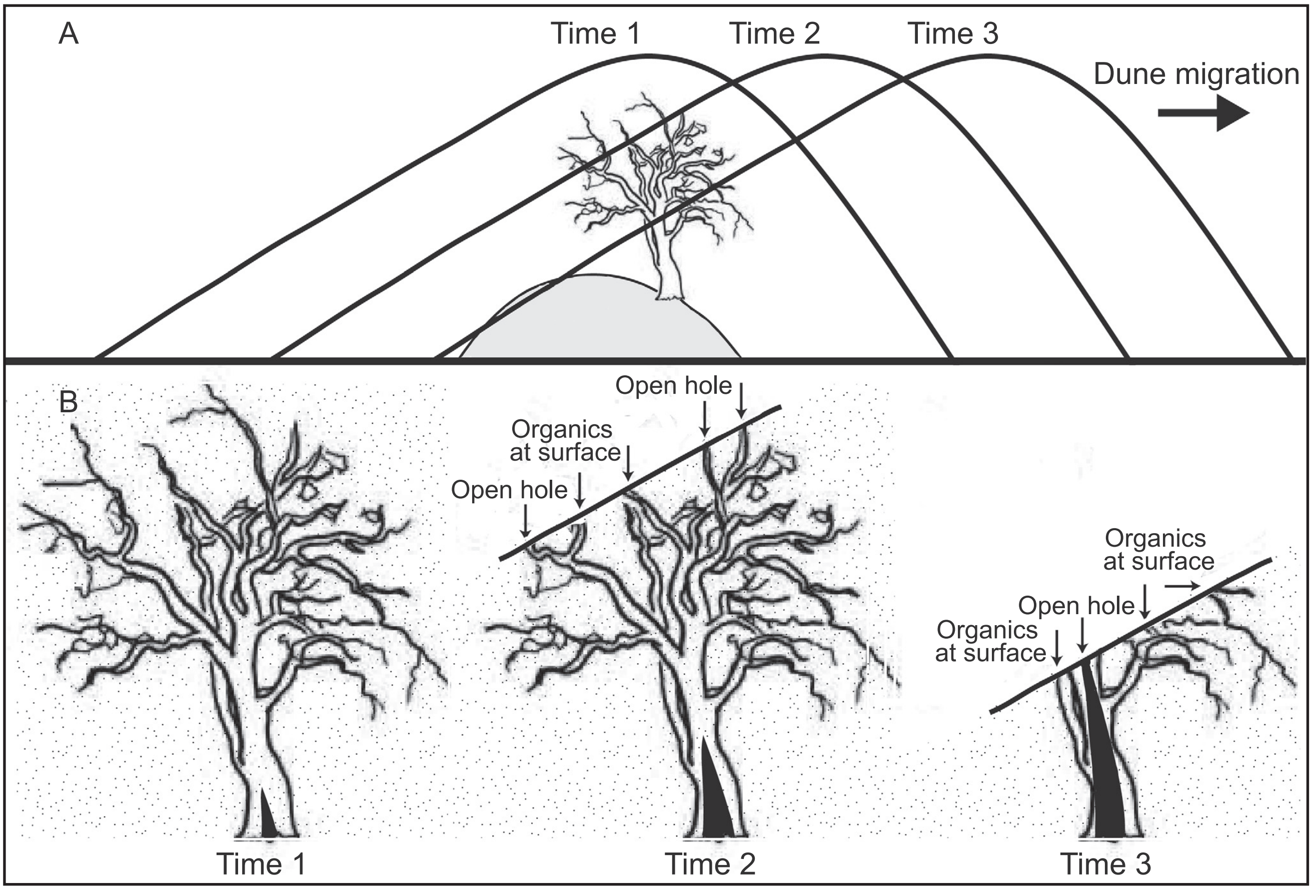

Fig. 11. Schematic diagram suggesting a possible model for the formation of a deep, vertical dune decomposition chimney. (A) Changes in the position of the buried trees relative to the surface of the stoss slope and exposure of the paleosol. (B) The effects of ongoing vertical erosion of the stoss slope and upward progressing internal decay through time. Areas buried within the dune are represented by the stippled texture.

and deeper holes occur when erosion of the stoss slope intersects the fully decomposed trunk of a buried tree, as at Time 3 (Fig. 11). The large diameter oak trees of Northwest Indiana could produce potentially hazardous holes versus other tree species with smaller diameters. While many questions remain to be explored regarding rates of decomposition within a fully buried tree, one major implication of this study is that fungal activity does not go dormant once the tree is buried; it continues and is likely enhanced by Ca available in the surrounding sediments and from Ca- and Mg-rich pore waters at this site.

5. Conclusions

Collectively, the data support the following model for the development of dune decomposition chimneys at Mount Baldy – collapse features caused by the decay of trees that were buried by an encroaching dune.

(1) The coastal landscape at Mount Baldy consisted of a system of stabilized late-Holocene parabolic dunes overlying post-Nipissing nearshore deposits. The restriction of sediment supply by the installation of harbor structures left the shoreline at Mount Baldy vulnerable to ongoing erosion in the 19th and 20th centuries owing to a combination of anthropogenic factors (sand mining and recreational activity that reduces natural vegetation) and natural processes (lake-level variability, storm-induced wave action, wind action, changes in winter ice shelf, and the presence and distribution of vegetation).

(2) Dominant onshore winds initiated the rapid north–south migration of the dune form that buried mature trees including black oaks, as it moved. The modern Mount Baldy therefore consists of historically transported aeolian sediments overlying the stabilized late-Holocene landscape with mature oak trees (*Quercus* spp.) entombed in the internal dune stratigraphy.

(3) Individual trees contained fungal communities consisting of saprotrophic wood decay fungi that were already actively decomposing the internal structure of the trees at the time of burial. Fungal activity continued after burial with decomposition occurring most rapidly at the base of the trunk and extending upward to create an inverted conical void toward the point of branching.

(4) After burial, the biomineralization of a calcium-carbonate-rich authigenic cement progressed at the contact between the organic material of the tree and the surrounding sands, facilitated by fungi that utilize Ca in the building of their hyphae. At this site Ca is available from multiple sources including (1) local sediments dominated by quartz (~70%) with lesser amounts of K-feldspar (10%) and dolomite (15%), (2) clasts of Ca-rich and Mg-rich fossiliferous back-barrier lacustrine sediments that are sourced from an exposed layer at the modern beach and transported up the stoss slope by onshore winds, (3) Ca-rich and Mg-rich atmospheric water that is the source of interstitial pore water in aeolian sediments. The biomineralization of the calcium-carbonate-rich cement lends stability to the sands directly encasing the buried trees.

(5) Continued migration of the dune form and erosion of the stoss slope reduced the height of the sand layer covering the buried trees. Horizontal forces on the buried trees are assumed to be negligible after full burial, but changes in the elevation of the stoss slope would cause vertical forces to vary through time. As the dune surface lowered to the level of the initial forest canopy, it eroded into decomposing limbs and toward the upper portion of tree trunks. Precipitation supplied Ca- and Mg-rich water that continually funneled preferentially along the conduits provided by the buried and decaying organic matter.
(6) Continued internal decomposition eventually caused the collapse of segments of organic matter, leaving open voids temporarily stabilized by the calcium-carbonate-rich cement. Limbs having dip angles that intersected the stoss slope produced holes that were either visible at the surface or that were concealed by a thin veneer of sand (decomposition chimneys).
(7) Once disturbed, the holes readily infilled with sand leaving a seemingly undisturbed to dimpled surface.

The proposed model includes factors that are specific to the Mount Baldy dune, including local sources of carbonate. Investigation of similar holes or buried trees found in migrating dune systems in other locales like Silver Lake State Park, Michigan and the Oregon Dunes National Recreation Area, Oregon, provide an opportunity to assess the importance of various aspects of the mode. These aspects include the formation of the calcium-carbonate-rich cement, the rate of dune migration and erosion, environmental conditions within the dune, tree species, climate, and the composition of fungal communities. Additionally the study of a singular site cannot determine the possible role of sediment mineralogy, tree species or size, duration of burial, and local climate in the development of a dune decomposition chimney. Interestingly enough, this model could provide a possible mechanism for the formation of fossilized tree casts unearthed in growth position and preserved in the Pennsylvanian "fossil forests" of the Joggin Formation, Nova Scotia (Lyell and Dawson, 1853; DiMichele and Falcon-Lang, 2011; Grey and Finkel, 2011) and Quaternary eolianites in Bermuda (Rowe and Bristow, 2015).

Dune decomposition chimneys are collapse features formed when migrating dunes encroach on a forest and buried trees subsequently decay. This study provides what we know to be the first published peer-reviewed data and model to evaluate the formation, distribution, or persistence of such collapse features in aeolian systems. At Mount Baldy the majority of holes observed were created from small-diameter tree limbs and were <1 m in depth, posing an environmental nuisance rather than a hazard. Still where continued vertical erosion intersected a void created from a vertically oriented tree trunk, dune decomposition chimneys could present a potentially unseen geologic hazard in heavily visited natural areas, as was the case in 2013 at Mount Baldy. It is still our operating hypothesis that the boy was sustained by an air pocket; suggesting that he did not slide to the base of the hole and rather that there was void space beneath him. This idea could possibly be investigated by geophysical observations from the accident site but the geologic integrity of the area may have been compromised during the rescue. Because migrating dune systems are observed in many coastal and inland areas, the data presented in this study may aid in preemptively identifying areas where environmental conditions could contribute to the formation of dune decomposition chimneys.

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